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Load Distribution Analysis for Weight and Ballistocardiogram Measurements of Heart Failure Patients using a Bed Scale

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Abstract—**Ballistocardiogram (BCG) is an emerging tool with the potential to monitor heart failure (HF) patients. A close association of the weight to the BCG as an intermediate signal source requires a careful design, where events such as saturation of the weight signal can result in the loss of the BCG. This work closely examined the factors around the weight while load cells placed under each support of a bed collected the BCG (e.g., body weight, distribution over the four supports of the bed). Following the calibration of weights based on the location of the polls, the study examined the ratios of loads in head-foot and lateral directions. The head-foot ratio was also correlated to the height. Twelve non-obese HF patients were recruited, and the weight and BCG were appropriately measured, where the average error of the weight measurements was 0.45 ± 0.30%. The mean ratio of the loads between head to foot sensors was 3.2 ± 0.7 with a maximum ratio of 4.5, showing that the head-ward sensors supported greater body weight. The ratio of the loads between the right to left sensors was 1.2 ± 0.1. The height and the head-to-foot ratio had an inverse correlation (r = 0.52). Based on the analysis, the head-ward sensors should have a higher capacity of up to three times that of the foot-ward sensors to prevent any signal saturation. Mobility issues were observed in some subjects, attributing to the lateral imbalance. These novel findings based on the end-users (i.e., HF population) may allow better allocation of conditioning resources to obtain the BCG (e.g., optimally adjusted sensitivity).**

I. Introduction

Heart failure (HF), which is defined as the inability of the heart to sufficiently circulate blood, affects more than 660,000 people over 40 years of age in Canada, with more than 50,000 new cases emerging annually, costing $2.8 billion per year [1], [2].

Strategies such as self-management are implemented to reduce the healthcare cost and provide better care for patients, where patients are asked to assess their vital signs such as weight daily and report any such increases. While self-management has been shown to have the highest benefit-to-risk ratio among the available treatments of HF, and the lack of it is associated with increased mortality and hospitalization, the low rate of patient adherence limits clinical effectiveness [3].

Zero-effort technology (ZET), defined as a type of technology that requires zero or close to zero effort from the user, may provide a means to monitor the patient in an ambient and unobtrusive manner, mitigating some of the non-compliance issues by shifting the burden from the user to the technology [4]. Ballistocardiogram (BCG), which is defined as the mechanical vibration due to ejection of the blood and the subsequent circulation, has been studied extensively as a potential tool to provide unobtrusive monitoring of HF patients [5], [6]. One of the several techniques to acquire the BCG involves further processing the weight signal obtained by force sensors (e.g., load cells) [7], [8]. The loss of this intermediate signal through events such as signal saturation prevents the proper acquisition of the BCG. While some of the applications, such as weight scale modality, are relatively robust to these events given its single platform mechanism, further examination is required when multiple supports are used.

In this work, zero-effort bed scale sensors have been developed to unobtrusively measure the weight and ballistocardiogram (BCG) of individuals with HF. While there have been applications of using load cells under the bed polls to collect the BCG, there are limited studies that examined the weight distribution across the supports and their effect as an intermediate signal on measuring the BCG. There is also limited evaluation of the technology on the clinical population [9]. To the authors' knowledge, this work is the first study that examined the load distribution factors in the setting of using four supports to acquire the weight and BCG on an HF population.

II. Methods

In A bed prototype was used to investigate the weight distribution and its effect on the acquisition of the BCG. This section presents the specification of the prototype used is illustrated first, followed by the data analysis.

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A. Prototype Design

The prototype consisted of two components: the sensor and conditioning circuit. Load cells typically found in a weight scale (EX204, Shenzhen Exact Sensor Instrument Co., Ltd, Shenzhen, China; 50kg rating) were installed on a custom-made bracket that relayed the force between the bed and sensors. The bracket was fixed on the bed frame leg using an aperture and had two load cells attached to the bottom. Square pockets were made on the bracket bottom to suspend the centerpieces of the load cells so that any applied force could bend the attached strain gauge for transduction. Details of the bracket are illustrated in Fig. 1. Further details of the load cell functionality and the bracket design can be found in the previous work [7]. Two load cells supporting each leg formed a Wheatstone bridge, each capable of supporting up to 100kg. A total of eight load cells that could bear 400kg load supported the four legs of the bed.

The bridge signal was amplified by an instrumentation amplifier (AD8221, Analog Devices) with a gain of 496 and reference of 0V. Four sets of the conditioning circuits shown in Fig. 2 were used to process the four signals coming from the bed legs, and AC components were combined in the subsequent stage using a summation amplifier with a gain of 200 to retrieve the BCG (AD8599, Analog Devices). Note that the total gain was determined based on the previous work [7]. Also note that the conditioning circuit in Fig. 2 was sufficient to retrieve the BCG, thus further processing of the BCG was excluded for brevity.

B. Weight Calibration

Once the four signals were digitized using an analog to digital converter (AD7656, Analog Devices) with the sampling frequency of 1000Hz, the voltage values were converted into weights. Namely, each leg's weight per voltage ratio was calculated by dividing the load applied by the amount of the voltage change from the baseline (i.e., no load).

Three different loads were used preliminarily to calculate the voltage to weight ratio: the bed without load, the bed with a male participant, and the bed with a female participant. Note that these participants were not part of the HF population who used the bed scale during the clinical trial. HF population was not used for the calibration as part of a test set.

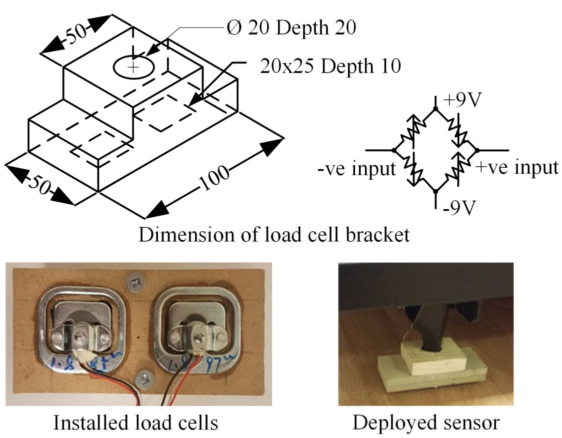

Figure 1. Load cell bracket dimensions in mm for each leg (top) and the device after the installation (bottom)

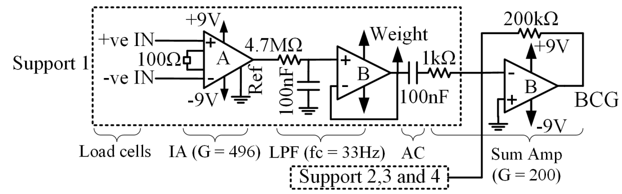

Figure 2. Conditioning circuit for the weight and BCG. A: AD8221, B: AD8599, IA: instrumentation amplifier, G: gain, LPF: low-pass filter, fc = cut-off frequency, AC: AC coupling, Sum Amp: summation amplifier

The weights of the bed, male, and female participants were 27.4kg, 72.1kg, and 54.9kg, respectively. A weight scale was put under each leg to measure the gold-standard weights (i.e., true loads applied to each leg). Each leg had three constants based on the three loading scenarios, which were then averaged to give the final value for each leg. Note that the gold-standard measurements for each leg were not available for the HF population, as explained below.

C. Bed Dimension and Placement of the Sensors

While each leg support was capable of handling up to 100 kg, the distribution of the weight of the bed and occupant across the supports determined the actual load capacity. It was observed that the legs of the bed frame were located slightly indented from the edge of the frame, as shown in the top diagram of Fig. 3. Namely, further inward placement of the head-ward sensors in effect placed a higher load on them. A simple uniform bar model was used to calculate the weight distribution, and its free body diagram is shown in the bottom diagram of Fig. 3. It was assumed that the bed was symmetric on both sides, and only the loads in the head-to-foot direction were different. Note that the weight of the sheet and pillow was relatively minor and not incorporated in the model. The ratio between the forces on the head-ward sensor and the foot-ward sensor was derived using the static equilibrium of the forces and torques applied to the supports.

To achieve the static equilibrium, equations in (1) had to be satisfied. The expanded forms of the equations are (2) through (4). By solving for F_H over F_F, the ratio was obtained in (5).

$$\sum F = 0, \sum \tau_A = 0, \sum \tau_B = 0 \tag{1}$$

$$\sum F = 0 = F_H + F_F - F_M \tag{2}$$

$$\sum \tau_A = 0 = F_M\left(\frac{L}{2} - d_T\right) - F_H\left(L - d_T - d_H\right) \tag{3}$$

$$\sum \tau_B = 0 = F_T\left(L - d_T - d_H\right) - F_M\left(\frac{L}{2} - d_H\right) \tag{4}$$

$$\frac{F_H}{F_F} = \frac{L - 2d_F}{L - 2d_H} \tag{5}$$

As illustrated in Fig. 3, d_H, d_T, F_H, and F_F are the indented distances of the head-ward and foot-ward sensors and the reaction forces by the head-ward and foot-ward supports, respectively. L is the length of the bed. τ_A and τ_B are the torques generated at points A and B, respectively. The ratio of F_H and F_F based on the dimensions was 1.348. The head-ward and foot-ward sensors theoretically supported 57.4% and

42.6%, respectively. The weight distribution could be normalized by dividing the head-ward load by the ratio of 1.348. The adjusted loads could be used to study the distribution of the weights. Based on the weight of the bed, a single head-ward and foot-ward sensors ideally bore 7.9kg and 5.8kg of the bed weight, leaving 92.1kg and 94.2kg for the occupant. The actual weights loaded on the head-ward sensors were 8.2kg (right) and 7.6kg (left), and that on the foot-ward sensors were 5.0kg (right) and 6.6kg (left), approximately in agreement with the theoretical values given the minor skewness in the bed frame.

E. Weight Distribution Calculation and BCG Acquisition

Each leg had two voltage values corresponding to the bed's weight and the combined weight of the occupant and bed. The difference between the two measurements was multiplied by the voltage to kilogram constant previously calculated, followed by the summation of all four weights on the supports to provide the weight of the participant. Finally, the error of the measured weight compared to the true weight, collected by the participant standing on a weight scale, was calculated.

In addition to the participant's weight, the ratios between left-right and head-foot loads for each trial were calculated to study the body weight distribution. The head-ward weights were divided by the calibration ratio specified above (i.e., 1.348) to adjust for the bed structure. Left-right and head-foot distribution ratios were then calculated where the two values corresponding to each side were averaged. Finally, the ratio was correlated with the height of the subjects.

The BCG was examined in comparison to the ECG to validate its periodic nature.

E. Data Collection

Older heart failure patients (i.e., 65 years of age or older with New York Heart Association HF class I or II) were recruited. While the system could potentially accommodate patients with a wide range of weights, this study focused on non-obese patients with less than 30 kg/m^2 body mass index (BMI). Obese patients with the BMI greater than 30 kg/m^2 were thus excluded for future evaluation.

Each participant laid down on the bed for five minutes on his or her back (i.e., supine position; see Fig. 3). One hundred seconds of clean data within the five-minute interval was selected for the weight and BCG. The voltage samples were averaged for the weight calculation. As well, the same amount of the weight measurement without the participant (i.e., only with the bed) was selected and averaged. The length of one-hundred seconds was used as an initial investigative feature that is long enough to eliminate the white noise in the signal. An example voltage signal of a single leg sensor is shown in Fig. 4. All trials took place in the HomeLab at Toronto Rehab Institute, Toronto, Ontario, Canada, and the study was approved by the institutional research ethics board (REB 13-6901). The data was collected as a part of a more extensive study. However, only the relevant parts were included here for brevity. Readers are referred to the past works for more details [10], [11].

III. RESULTS

A total of 12 older adults with HF participated in the evaluation of the bed. There were eight male and four female participants with a mean age of 75.4 ± 5.9 years.

The study adequately measured the weight and BCG of the occupants with the voltage to weight ratios (kg/V) of 11.1, 11.5, 10.9, and 10.6 for head-right, head-left, foot-right, and foot-left, respectively. The average error of the weights of 12 measurements was 0.31 ± 0.22 kg, which is 0.45 ± 0.30%. On average, the ratio of the weight loads between the head- and foot-ward sensors after the indentation adjustment was 3.2 ± 0.7, and the ratio of the right to left loads was 1.2 ± 0.1. The results are summarized in Table I. Successful acquisition of BCG was made as illustrated by Fig. 5.

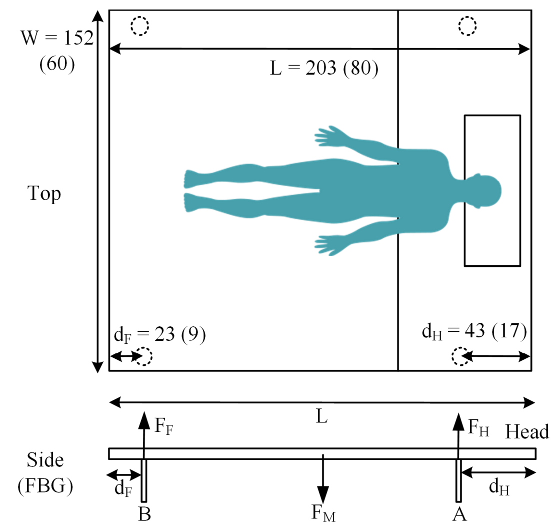

Figure 3. The participant on the bed with four supports (top). Free body diagram of the related forces (bottom). Units are in cm (inch).

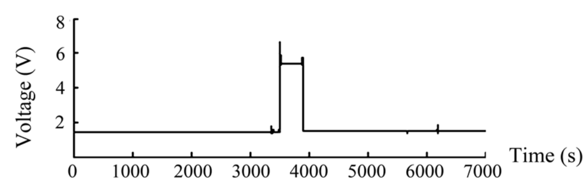

Figure 4. A voltage signal of a single bed leg showing the regions without the participant and with the participant (Participant 14)

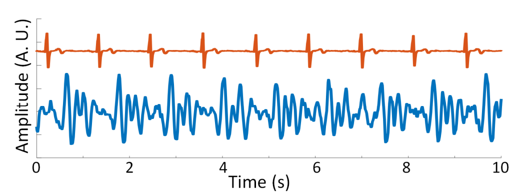

Figure 5. BCG in comparison to ECG (Participant 2)

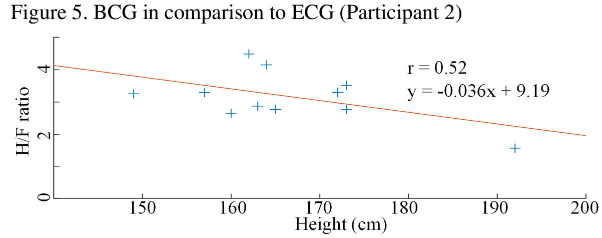

Figure 6. Inverse relationship between the height and the head to foot load ratio (H/F ratio: head to foot load ratio)

TABLE I. SUMMARY OF WEIGHT DISTRIBUTION

ID	W	E	R/L	H/F	ID	W	E	R/L	H/F
2	75.4	0.38	1.3	2.8	41	70.4	0.07	1.0	2.7
7	72.3	0.27	1.0	3.3	65	63.8	0.50	1.1	4.1
13	50.2	0.30	1.1	3.3	66	69.7	0.32	1.1	4.5
14	60.1	0.29	1.2	3.3	97	67.4	0.07	1.2	3.5
27	80.9	0.51	1.0	2.8	101	70.9	0.11	1.4	1.6
31	63.1	0.16	1.3	3.3	Mean	67.6	0.31	1.2	3.2
40	57.4	0.14	1.4	2.9	SD	8.2	0.22	0.1	0.7

W: Measured weight in kg; E: Error in kg; R/L: Right to left ratio; H/F: Adjusted head to foot ratio

The correlation coefficient between the height and the adjusted head-to-foot load ratio was 0.52, showing an inverse relationship between the two (Fig. 6).

IV. DISCUSSION

The current study revealed several key design elements to be considered. The most notable finding of the analysis was that the portion of the body weight placed on the head-ward sensors was more than three times greater than that placed on the foot-ward sensors when adjusted for the support locations. A decrease in height induced a more unbalanced ratio. This pattern is expected as the subject places the head on the pillow near the edge of the bed. As a result, one should expect a heavier load of the body weight to be placed on the head-ward sensors. Note that the actual loads placed on the sensors were unadjusted loads. In this study, a further indentation of the head-ward sensors increased the actual load significantly. The average unadjusted ratio in the head-to-foot direction was 4.3 ± 1.0, with the maximum ratio reaching 6.0. Conversely, if the reverse is the case (i.e., further inward placement of the foot-ward sensors), the balance will be shifted towards the opposite end. Equation (5) may be used to calculate the specific load distribution in individual cases.

It was shown that the left-right load ratio was also unbalanced. While the broad width of the bed was a reason for the imbalance (i.e., participant was not precisely centered), it was also due to the mobility issues in HF patients. Namely, patients with mobility issues had difficulty moving towards the center of the bed, in which case the participants remained off-centered for the duration of the recording. The mobility factor would have been obscured if normal healthy participants were involved and could be revealed only via the involvement of the patient population.

A 100-second interval to average the weight signal was sufficiently long to provide a representative mean. While it is difficult to specify the shortest amount of time used, the interval can be much shorter, presumed that the participant remains still.

To achieve the goal of measuring the BCG using force sensors under the bed supports, proper design of the load capacity is vital as the saturation of one sensor renders the BCG unusable. The contribution of this work may provide helpful insight in developing a prototype to collect the BCG. For example, hardware resources could be allocated efficiently to accommodate unique sensitivity and capacity required for each support. The height to load ratio could be used in an algorithm to customize the system to best suit the individual's characteristics. If measuring signals of all supports is not an option, one can design the position of the poles (i.e., load bearing) so that the installed sensors bear much of the weight, thus the BCG. Note that findings in this work are being implemented in the next iteration of the prototype in the authors' work.

A limitation of the work was that the calibration ratio used was based on theoretical calculation. The weights subtracted from the total weights were the actual weights, which may have created a minor discrepancy. However, the effect on the results is likely negligible and do not affect the assessments made in this work.

There are several directions for future research. While this study examined older adults with HF with less than 30 kg/m^2 of BMI, obese HF patients should be included to reflect the wide range of weight of the HF population. Future studies should also investigate ways to decrease the measurement error below 0.5%, which can be achieved through better calibration involving more participants and accounting for minute non-linearity that may be present in the sensors as seen in the conversion ratios. During the analysis, it was observed that the voltage of the weight signals reached close to the maximum range; thus, the gain of the instrumentation amplifier may be lowered to accommodate heavier weights. In a clinical setting, retrieving the correct change in weight is also essential to assist HF patients and should be investigated next.

V. CONCLUSION

This study examined the distribution factor associated with the weight and BCG measurement using a bed scale. The system measured the BCG and weight of older adults with HF with 0.45 ± 0.30% accuracy. It was shown that the head-ward sensors had about three times higher load than foot-ward sensors, which should be incorporated in the design specification of a bed scale. The equation derived in this work could be used to quantify the uneven load distribution.

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